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Nuclear Reactor Doubling Time Calculation Using FIR Filter

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Abstract

In nuclear reactor engineering, reactor doubling time is generally applied to indicate the change of power level and usually provided by a nuclear instrumentation system (NIS). In a digital NIS, current signal from neutron detector is pre-amplified and conditioned into voltage signal which is proportional to the power level of nuclear reactor, and then is acquired and processed by a digital computer in the NIS. The measurement noise contained in the acquired voltage signal will cause a lot of uncertainty in the reactor doubling time calculation result. In this paper, the sensitivity analysis of nuclear reactor doubling time calculation is investigated. A calculation algorithm of reactor doubling time for digital NIS is proposed based on FIR Filtering techniques, and two filtering schemas to calculation reactor doubling time are given based on the FIR filter. A Hard-In-Loop (HIL) experiment environment was built to verify the discussed calculation algorithm. The experimental results show that the calculation algorithm developed can suppress the influence of measurement noise on calculation result to recover the signal's original features, and can provide us with good on-line calculation result.

Keywords: Digital nuclear instrumentation system; Reactor period; Reactor doubling time; Sensitivity analysis; FIR filter; Measurement noise suppression;

1. Introduction

Reactor period is a very important concept in nuclear reactor engineering, and it is an essential parameter for nuclear reactor control and protection system in all types of nuclear reactors. A short

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reactor period means the neutron flux or power level in nuclear reactor increases too fast. If the period is less than its set-point value, it is necessary to trigger a reactor trip protection action to shut down the reactor. If the calculation of reactor period is not timely and accurate enough, it is likely to cause some nuclear accident or suspicious shutdown. Therefore, reactor period is a very important parameter directly related to reaction operation and safety, and it has to be monitored by a set of dedicated equipment. [1]

In nuclear reactor engineering, the reactor doubling time is usually used to indicate the change of power level. During the reactor startup phase, nuclear reactivity is controlled by limiting the value of reactor doubling time.

In this paper, we introduced a Finite Impulse Response (FIR) filter to the calculation of the reactor doubling time, two filtering schemas were applied and some comparisons were made. The FIR filter was used to filter the original sampled voltage signal and its derived relative changing rate. With the FIR filter, a real-time on-line calculation algorithm of reactor doubling time was implemented.

Our experimental results of Hard-In-the-Loop (HIL) show that the calculation algorithm developed in this paper can provide us with good on-line calculation result of the reactor doubling time and is of good real-time performance.

2. Nuclear reactor doubling time calculation and its sensitivity analysis

2.1. Definition of nuclear reactor doubling time

Nuclear reactor doubling time is defined as that amount of time, normally in seconds, required for neutron density (power) to change by a factor of 2.

$$n = n_0 \cdot 2^{\frac{t}{T_d}} \tag{1}$$

Where: n_0 is neutron density of nuclear reactor at t_0 time; n the neutron density at t time; T_d is reactor doubling time at t time.

From equation (1) we can see that nuclear reactor doubling time can reflect the state of nuclear reactor. When $T_d < 0$, nuclear reactor operates in a subcritical state; when $T_d = 0$, nuclear reactor in a stable state; when $T_d > 0$, nuclear reactor in a supercritical state.

2.2. Calculation of nuclear reactor doubling time

Taking the natural logarithm on both side of equation (1), we get

$$\ln(n) = \ln(n_0) + t \cdot \frac{\ln 2}{T_d} \tag{2}$$

Then we get the doubling time calculation formula by deriving equation (2)

$$T_d = \frac{\ln 2}{\frac{d[\ln(n)]}{dt}} \tag{3}$$

From formula (3), we know that reactor doubling time is inversely proportional to the derivative of the natural logarithm of neutron density.

2.3. Reactor doubling time calculation formula used in digital nuclear instrumentation system

The approximation of the derivative of the natural logarithm of neutron density in equation (3) can be calculated by the following equation

$$\frac{d[\ln(n)]}{dt} \cong \frac{\ln(n_k) - \ln(n_{k-1})}{t_k - t_{k-1}} = \frac{\ln \frac{n_k}{n_{k-1}}}{t_s} \tag{4}$$

Where: n_k, n_{k-1} is the *k*-th and *(k-1)*-th sampled neutron density respectively; t_s the sampling period in seconds.

So we get the approximate calculation formula of reactor doubling time in digital nuclear instrumentation system as the following equation

$$T_d \cong \frac{\ln 2 \cdot t_s}{\ln \frac{n_k}{n_{k-1}}} \tag{5}$$

In the digital NIS under discussion, current signal from neutron detector is pre-amplified and conditioned into voltage signal, and then it is acquired and processed by a digital computer of the NIS.

According to nuclear engineering theory, we know that the reactor power level is proportional to the reactor neutron density (or flux), and the output current signal of neutron detector is proportional to the reactor power level [2]. So the acquired voltage signal is also proportional to the neutron density. Then we have the following relationship and equation.

$$n \propto I \propto V \tag{6}$$

Where: I is the output current signal from neutron detector; V the acquired voltage at t time.

Then the following equation is obtained

$$\frac{n_k}{n_{k-1}} = \frac{V_k}{V_{k-1}} \tag{7}$$

Where: V_k, V_{k-1} is the *k*-th and *(k-1)*-th sampled voltage signal respectively.

From equation (5) and (7), we get the approximate calculation formula of reactor doubling time practically used in digital nuclear instrument system as follows

$$T_d \cong \frac{\ln 2 \cdot t_s}{\ln \frac{V_k}{V_{k-1}}} \tag{8}$$

2.4. Sensitivity analysis of nuclear reactor doubling time calculation

The change of neutron density in nuclear reactor is continuous; therefore, the sampled voltage signal in digital nuclear instrumentation system is also continuous. Using Taylor expansion formula and ignoring the higher order terms, we can obtain

$$V_k \cong V_{k-1} + \dot{V}_{k-1} \cdot t_s \tag{9}$$

Substituting equation (9) into equation (8), we get

$$T_d \cong \frac{\ln 2 \cdot t_s}{\ln(1 + \frac{\dot{V}_{k-1}}{V_{k-1}} \cdot t_s)} \tag{10}$$

In practice, the acquired voltage signal always contains measurement noise whose nature is usually difficult to know. The acquired voltage signal is the superposition of the actual voltage signal and measurement noise, as follows

$$V_{k-1} = V_{k-1}^{act} + \Delta_{k-1} \tag{11}$$

Where： V_{k-1}^{act} is the actual voltage signal; Δ_{k-1} the measurement noise.

Substituting equation (11) into equation (10), we get

$$T_d \cong \frac{\ln 2 \cdot t_s}{\ln(1+\frac{\dot{V}_{k-1}^{act}+\dot{\Delta}_{k-1}}{V_{k-1}^{act}+\Delta_{k-1}}\cdot t_s)} \tag{12}$$

In practical application, it usually meets $\frac{\dot{V}_{k-1}^{act}+\dot{\Delta}_{k-1}}{V_{k-1}^{act}+\Delta_{k-1}}\cdot t_s \ll 1$, so we obtain

$$T_d \cong \ln 2 \cdot \frac{V_{k-1}^{act}+\Delta_{k-1}}{\dot{V}_{k-1}^{act}+\dot{\Delta}_{k-1}} \tag{13}$$

From equation (13), we see that nuclear reactor doubling time T_d is mainly determined by V_{k-1}^{act}, Δ_{k-1}, $\dot{V}_{k-1}^{act}$ and $\dot{\Delta}_{k-1}$. When there is a high Signal Noise Ratio (SNR), i.e. $V_{k-1}^{act} \gg \Delta_{k-1}$, the calculation uncertainty is mainly affected by the measurement noise change rate $\dot{\Delta}_{k-1}$; otherwise if SNR is low, it is affected by the measurement noise and its change rate, i.e. Δ_{k-1} and $\dot{\Delta}_{k-1}$.

The change rate of measurement noise is related with its distribution, power and frequency characteristics.

In equation (13), there is a measurement noise change rate item $\dot{\Delta}_{k-1}$, so we can conclude that the impact of the measurement noise on reactor doubling time calculation result will be amplified. Especially when the measurement noise is of high frequency nature, its impact will be more obvious. The change rate of measurement noise plays a dominant role in the negative impact on the calculation result of reactor doubling time.

Therefore, the calculation result of nuclear reactor doubling time is very sensitive to high frequency measurement noise in the acquired voltage signal. The noise in the measurement signal will increase the signal processing difficulties, and will cause a large uncertainty in the calculation result.

Some appropriate stabilization measures (e.g. filtering) should be taken in reactor doubling time calculation process to suppress the influence of measurement noise on the calculation result. But if the measure is taken improperly, e.g. a big inertial constant is used, the change rate of calculation result will be slow, the calculation result will lack real-time property. So, the choice of stabilization measures should make comprehensive consideration and take the following factors into account: (1) The Compromise between measurement noise suppression and effective signal retention; (2) The credibility and real-time property of calculation result.

3. Finite Impulse Response filter Design

In signal processing, a finite impulse response (FIR) filter[3] is a filter whose impulse response is of finite duration, because it settles to zero in finite time.

For an *N*th-order discrete-time FIR filter, the output is a weighted sum of the current and a finite number of previous values of the input. The operation is described by the following equation, which defines the output sequence $y[n]$ in terms of its input sequence $x[n]$:

$$y[n] = \sum_{i=0}^{N} b_i x\left[n-i\right] \tag{14}$$

where: $x[n]$ is the input signal, $y[n]$ is the output signal, b_i are the filter coefficients, also known as tap weights, that make up the impulse response, N is the filter order; an Nth-order filter has $(N+1)$ terms on the right-hand side. The $x[n-i]$ in these terms are commonly referred to as taps, based on the structure of a tapped delay line that in many implementations or block diagrams provides the delayed inputs to the multiplication operations. (See Fig. 1)

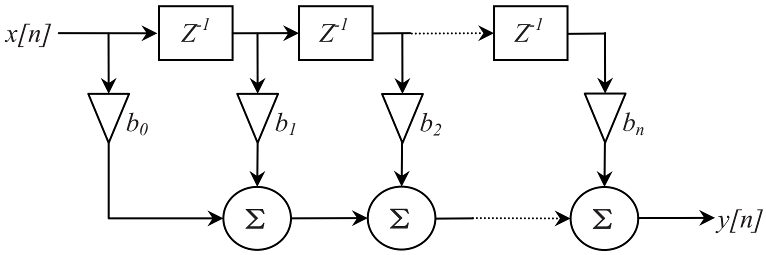

Fig. 1. A discrete-time FIR filter of order N

To design a filter means to select the coefficients such that the system has specific characteristics. The required characteristics are stated in filter specifications. Most of the time filter specifications refer to the frequency response of the filter.

In this paper, the Window Design Method[4][5] is used to find the coefficients. The Hamming Window (See Fig.2) is applied when designing the Nth-order discrete-time low-pass FIR filter.

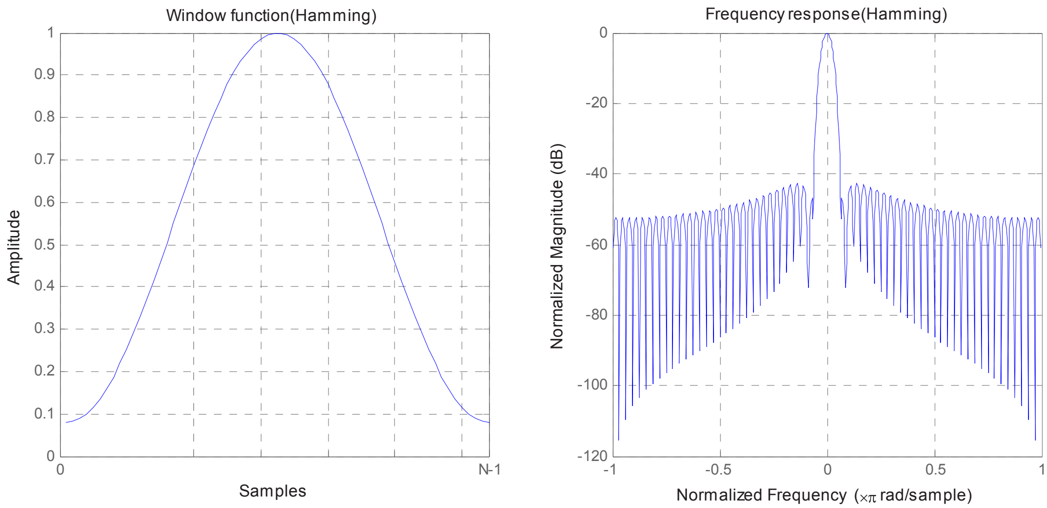

Fig. 2. (a) Hamming window function (b). Hamming frequency response

4. Two FIR filter schemas for reactor doubling time calculation

When we calculated the reactor doubling time based on FIR filter in this paper, two filtering schemas were applied.

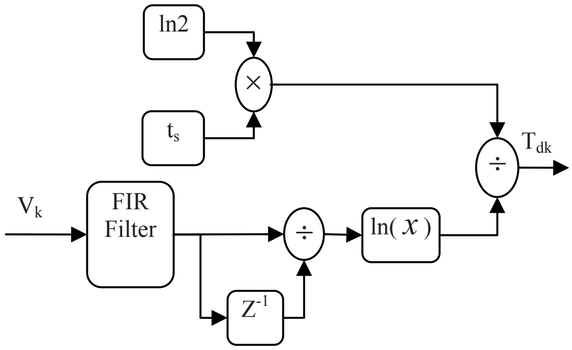

Fig.3. Filtering schema No.1

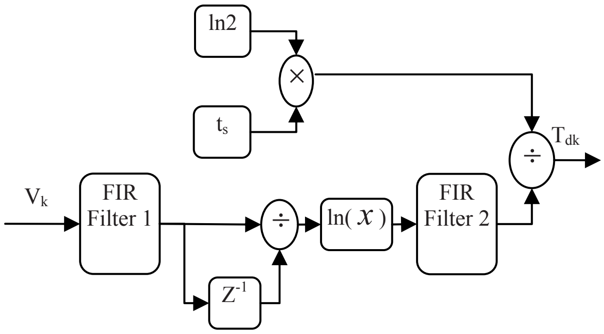

Fig.4. Filtering schema No.2

In filtering schema No.1, the FIR filter was used to filter the original sampled voltage signal only. While in filtering schema No.2, taking the sensitivity analysis of equation (13) into consideration, we used two FIR filter during calculating reactor doubling time, one for filtering the original sampled voltage signal and the other for filtering the natural logarithm of its relative change rate.

5. Experiment

In this section, we represented some experimental data and results to proof the correctness and effectiveness of the proposed calculation algorithm of reactor doubling time based on the designed FIR filter.

5.1. Experiment environment

A Hard-In-the-Loop (HIL) experiment environment was setup to verify the discussed reactor doubling time calculation. (See Fig. 5)

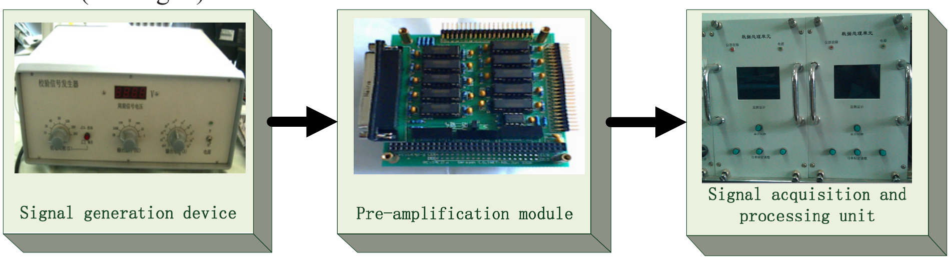

Fig. 5. HIL experiment environment

In Fig. 5, the signal generation device to provide current signal which emulates the output current signal from an actual ionization chamber detector.

The pre-amplification module is used for signal amplification, conditioning and isolation, in this module the current signal is converted into the voltage signal. The signal acquisition and processing unit consists of two parts: signal acquisition module and signal processing unit. The signal acquisition module in digital computer is used for signal A/D conversion and signal acquisition. The signal processing unit is used for signal processing, filtering, and then the reactor doubling time is calculated.

5.2. Experimental Results

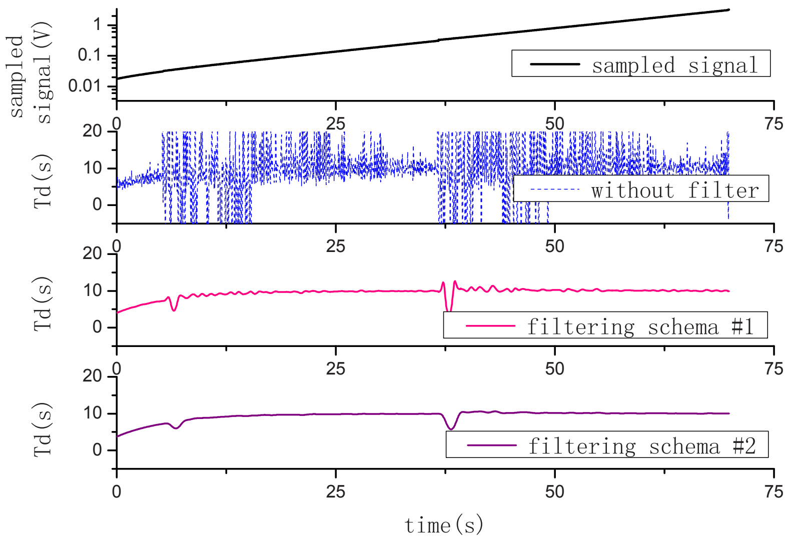

Fig.6. Experimental result with T_d=10s

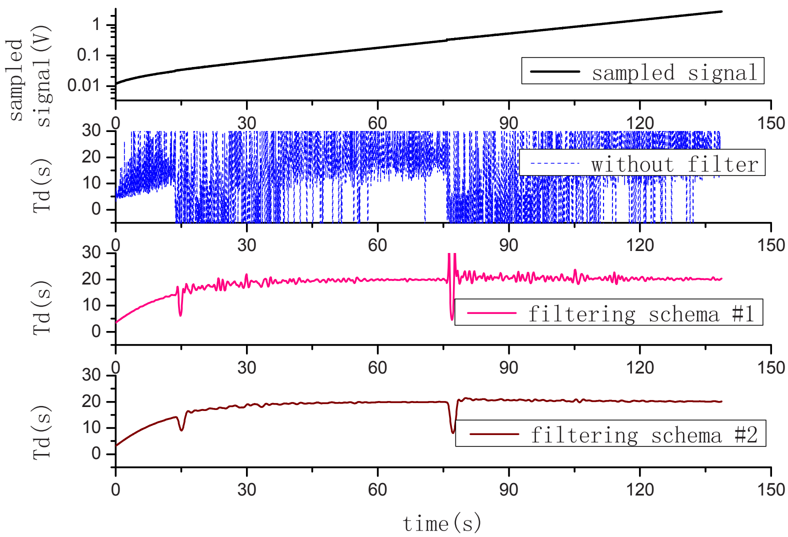

Fig.7. Experimental result with T_d=20s

In the experiments, the signal generation device generated a current signal with a reactor doubling time of 10 seconds and 20 seconds respectively which started with 10^{-9} mA and ended with 10^{-6} mA. The current signal was conditioned to the voltage signal with its value from 0.003 volt to 3 volt in the pre-amplification module.

The reactor doubling time was calculated in the signal processing unit using the two proposed filtering schemas discussed in section IV.

The experimental data processing result is given in Fig. 6 and Fig. 7.

It can be seen from Fig. 6 and Fig. 7 that the sampled voltage signal is always accompanied by some measurement noise, and the measurement noise is a major factor that causes a lot of uncertainty and randomness in the calculation results.

The results also show that the FIR filter-based algorithm for the estimation of reactor doubling time proposed in this paper is feasible and effective, and it can suppress the influence of measurement noise on calculation result to recover the signal's original features.

And the results show that the calculation result using filtering schema No.2 is much better than that using filtering schema No.1, because filter schema No. 2 takes into consideration the contribution of the measurement noise change rate to the calculation result.

6. Conclusion

In a digital NIS, current signal from neutron detector is pre-amplified and conditioned into voltage signal which is proportional to the power level of reactor, and then it is acquired and processed in the digital computer. The acquired voltage signal always contains measurement noise which has a great impact on the calculation result of reactor doubling time and causes a lot uncertainty in the result. In this paper, the sensitivity analysis of nuclear reactor doubling time calculation is investigated and the calculation algorithm of reactor doubling time for digital NIS is proposed based on FIR Filtering techniques. Two filtering schemas to calculation reactor doubling time were given based on FIR filter. A HIL experiment environment was setup to verify the discussed calculation algorithm. And we represented some experimental data and results to proof the correctness and effectiveness of the proposed calculation algorithm. The results show that the FIR filter-based algorithm for the calculation of reactor doubling time is feasible and effective, and it can suppress the influence of measurement noise on calculation result to recover the signal's original features.

Acknowledgments

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